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| Title: | Antarctic Ice shelf-ocean interactions in high-resolution, global simulations using the Energy Exascale Earth System Model (E3SM) |
| Author(s): | Asay-Davis, Xylar Storm<br>Comeau, Darin Scott<br>Hoffman, Matthew James<br>Maltrud, Mathew Einar<br>Petersen, Mark Roger<br>Price, Stephen F. Dr<br>Van Roekel, Luke<br>Veneziani, Carmela<br>Wolfram, Phillip Justin Jr. |
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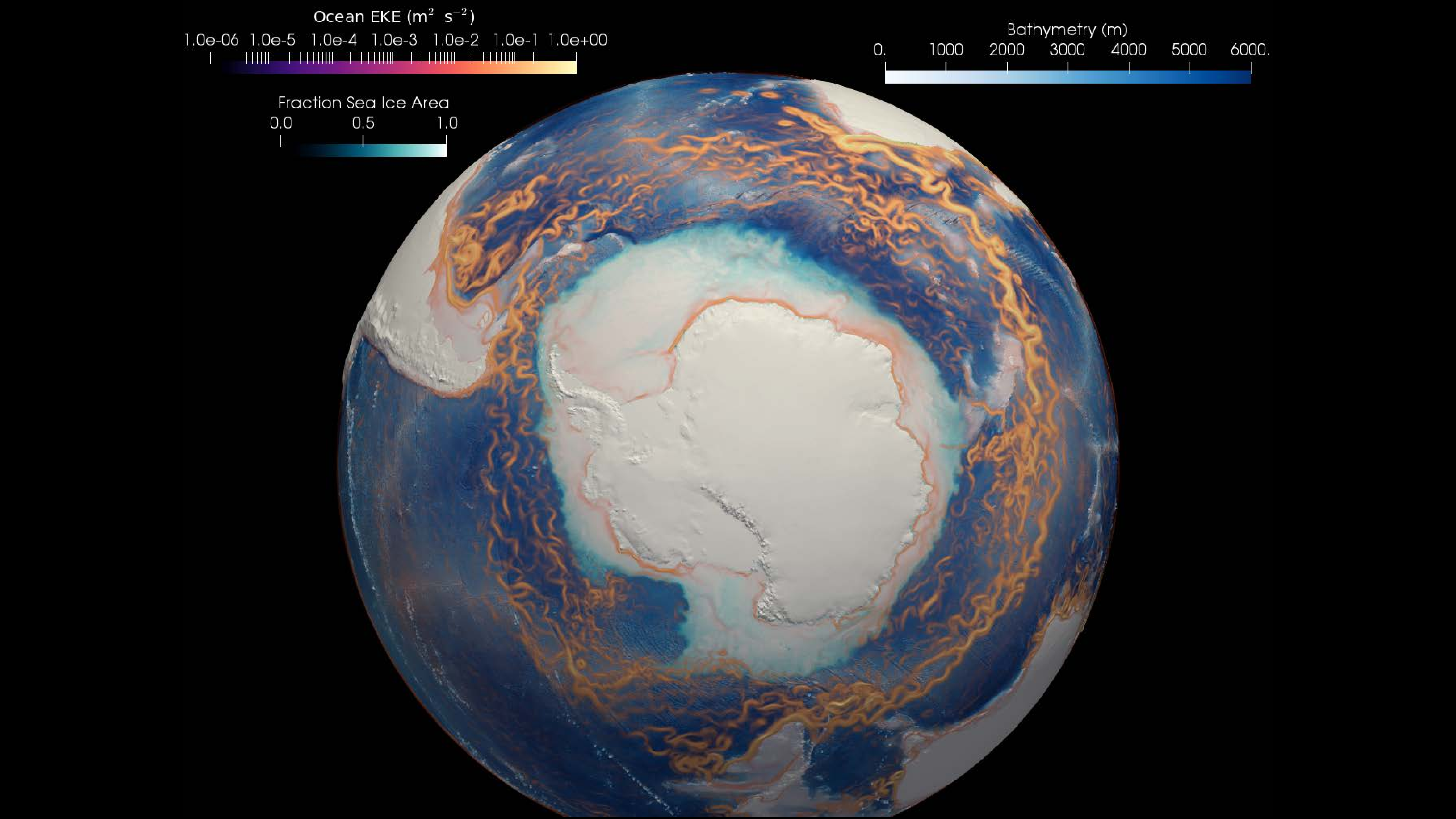
# Antarctic Ice shelf-ocean interactions in high-resolution, global simulations using the Energy Exascale Earth System Model (E3SM)

Xylar Asay-Davis, Darin Comeau, Matthew Hoffman, Mathew Maltrud, Mark Petersen, Stephen Price, Luke Van Roekel, Milena Veneziani, Phillip Wolfram

Los Alamos National Laboratory



Ocean EKE ($m^2$ $s^{-2}$)
1.0e-06 1.0e-5 1.0e-4 1.0e-3 1.0e-2 1.0e-1 1.0e+00
Fraction Sea Ice Area
0.0 0.5 1.0
Bathymetry (m)
0. 1000 2000 3000 4000 5000 6000.

# Outline

- E3SM model and project
- Ice shelf/ocean interactions in E3SM
- Land ice/ocean coupling in E3SM
- Summary

# Energy Exascale Earth System Model (E3SM)*

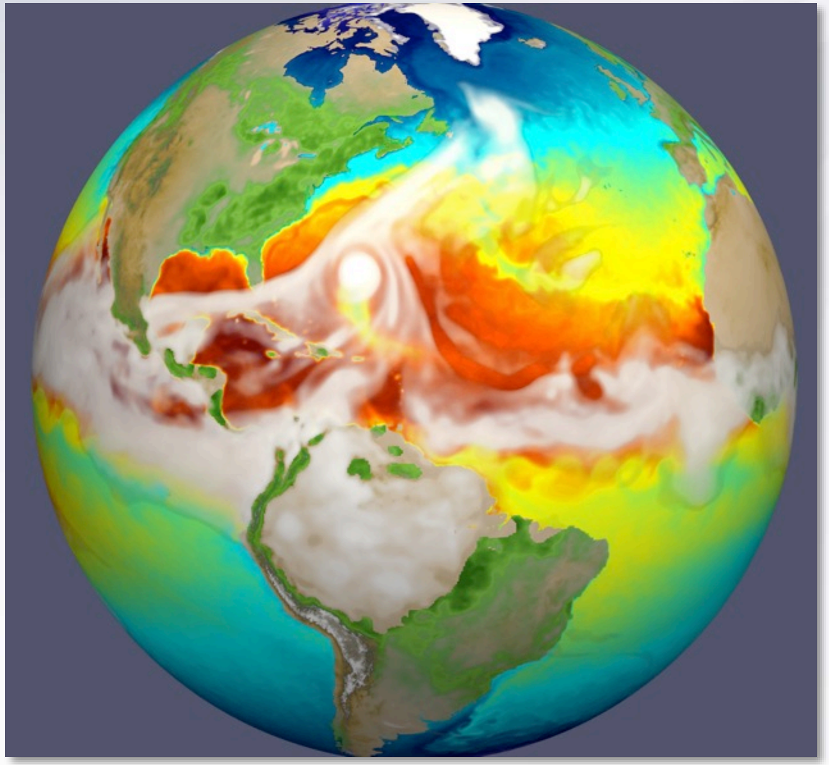
The U.S. Department of Energy (DOE) *E3SM* project aims to meet DOE and U.S. government agency needs for state-of-the-science Earth system modeling.

- *Phase 1:* July 2014 – June 2018
- *Public release:* April 2018
- *Phase 2:* July 2018 – June 2021

*Science focus areas:*

- Water Cycle
- Biogeochemistry
- Cryosphere:

  *How will the atmosphere, ocean, and sea-ice systems mediate sources of sea-level rise from the Antarctic ice sheet over the next 30 years?*



N. Atlantic hurricane in high-resolution configuration (color=SST)

* formerly the *Accelerated Climate Model for Energy (ACME)*

# E3SM Version 1.0 Release

Public release of v1 code and simulations ~6 weeks ago

- Project homepage (https://e3sm.org)
- Code available on Github (https://github.com/E3SM-Project/E3SM)
- Simulations (limited DECK) (https://e3sm.org/data/get-e3sm-data)

Highlights:

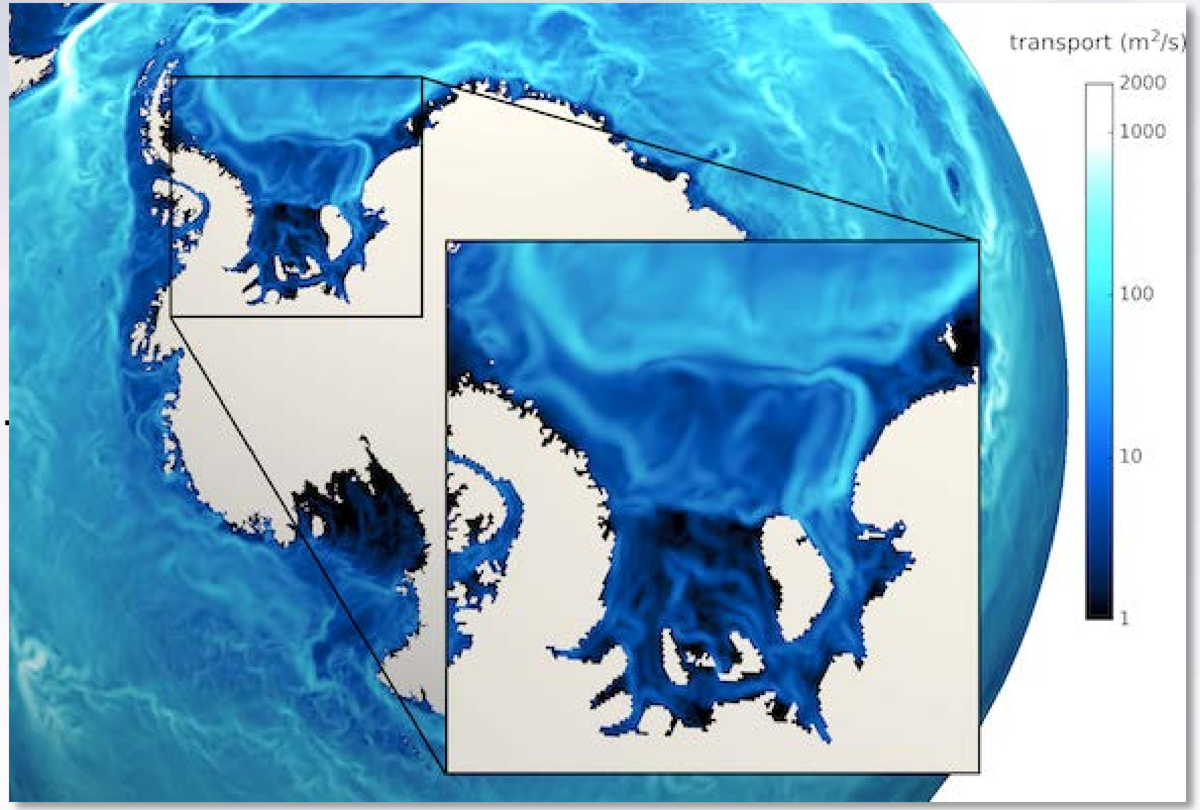
- open development
- variable resolution (all components)
- new ocean, sea ice, land ice models
- new var. res. analysis framework
- ocean circulation beneath ice shelves

  (currently unverified; unsupported)

# Cryosphere Simulations (ongoing)

Identical low (EC60to30km) & medium (RRS30to10km) resolution configurations, with & without Antarctic ice shelves:

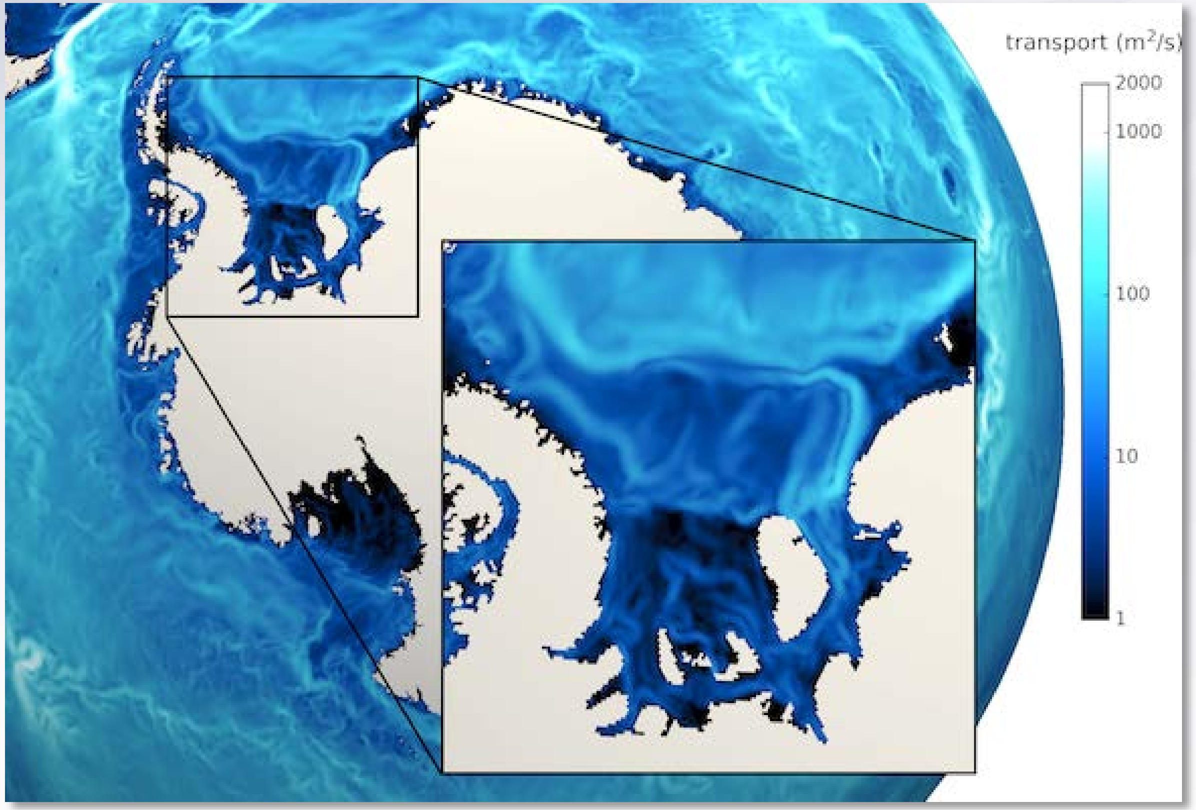
- Prescribed atmospheric forcing (multiple CORE-IAF cycles)
- Coupled atmosphere/land/ocean/ sea-ice pre-industrial (several cen
- Coupled atmosphere/land/ocean/ sea-ice historical (1850-present)




ocean transport in global, med. resolution simulation

# Cryosphere Simulations: Goals

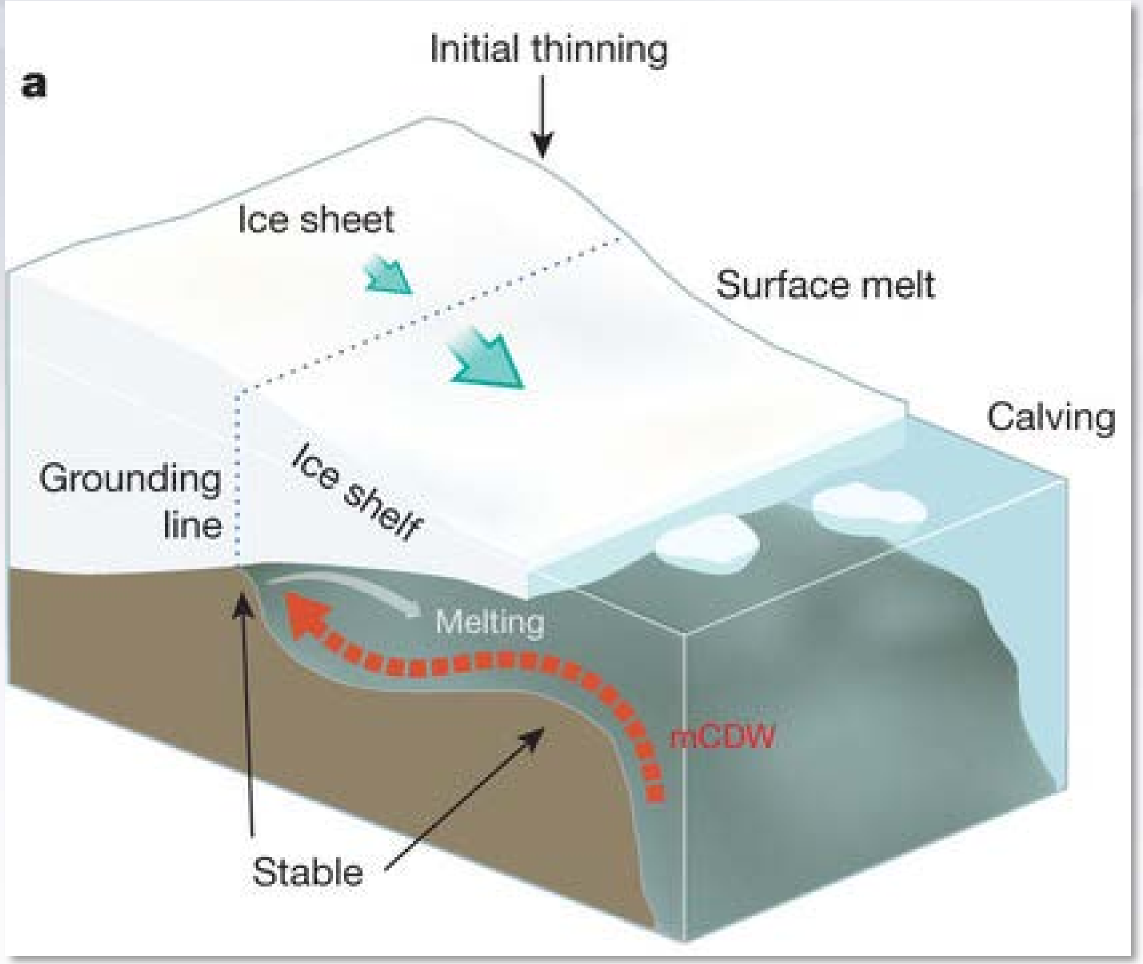
- Demonstrate ice shelves “do no harm” to global simulations
- Demonstrate sub-ice shelf melt rates and other relevant ice-sheet-proximal climate characteristics plausible relative to observations
- Explore sensitivity to (1) presence/ absence of shelves, (2) forcing and coupling, (3) resolution
- Release of CORE-IAF, pre-industrial equilibrium, and historical simulations by fall 2018




ocean transport in global, med. resolution simulation

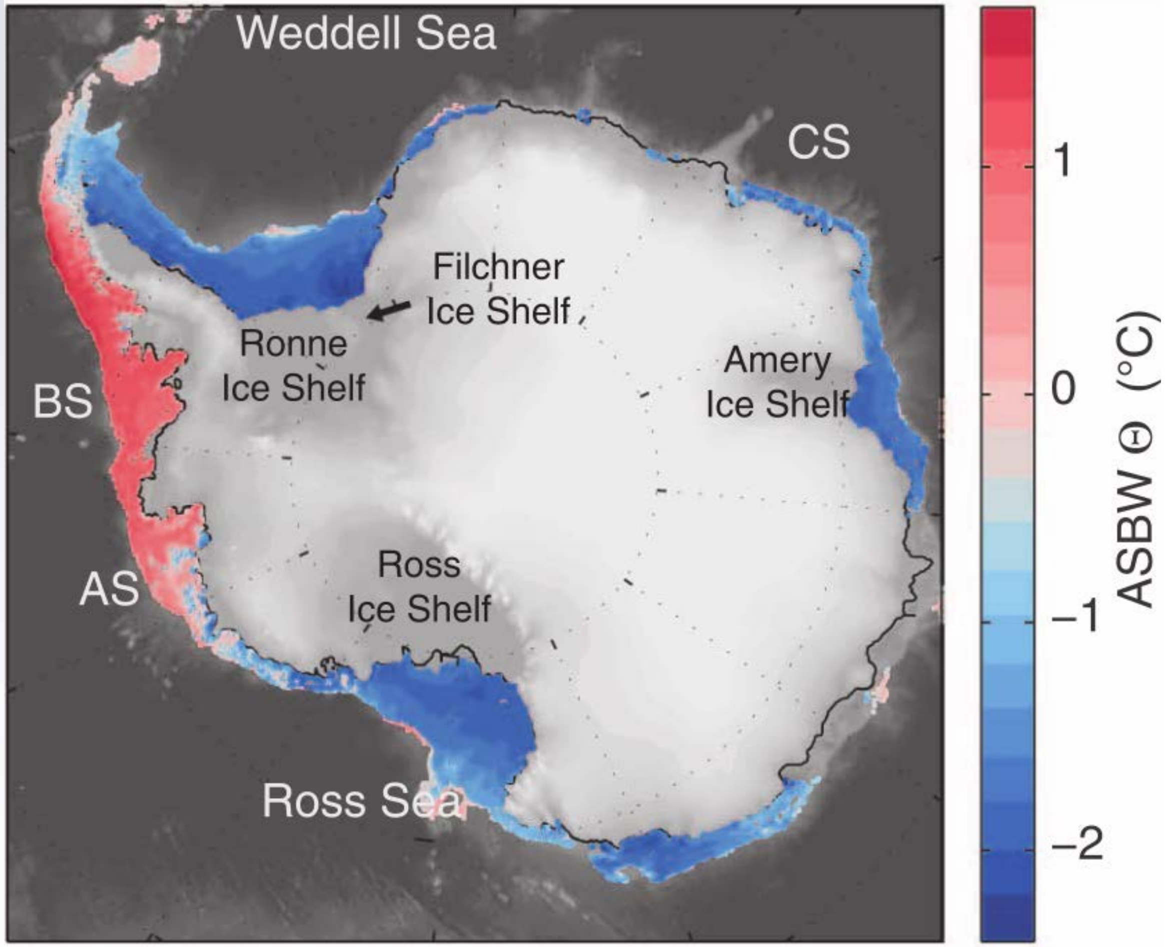
# Ice shelf/ocean interactions

- Ice shelves: floating extensions of ice sheets and glaciers
- Ocean waters flow into cavities below ice shelves
- Temperature of inflowing water determines the amount of melting (nonlinear effect)

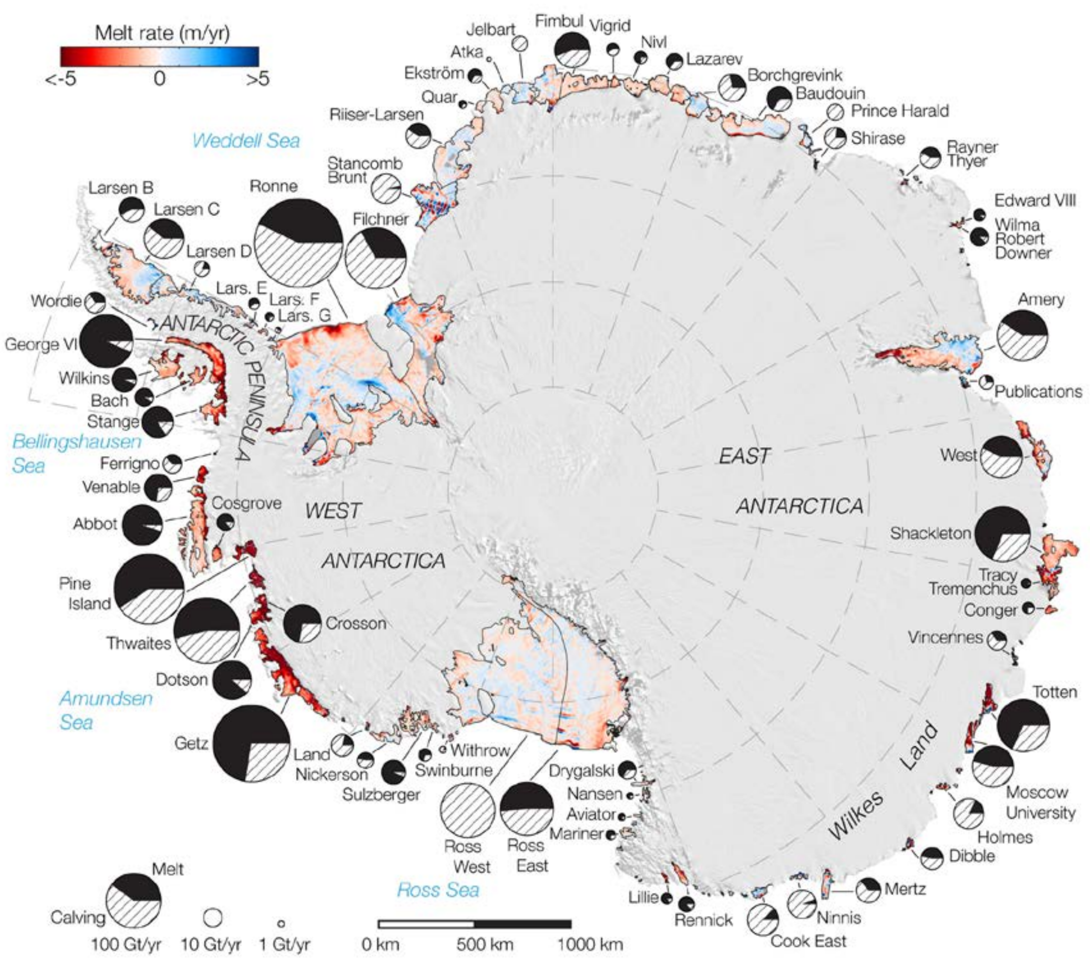



From Hanna et al. (2013)

# Observed Bottom Temperature and Melt Rates

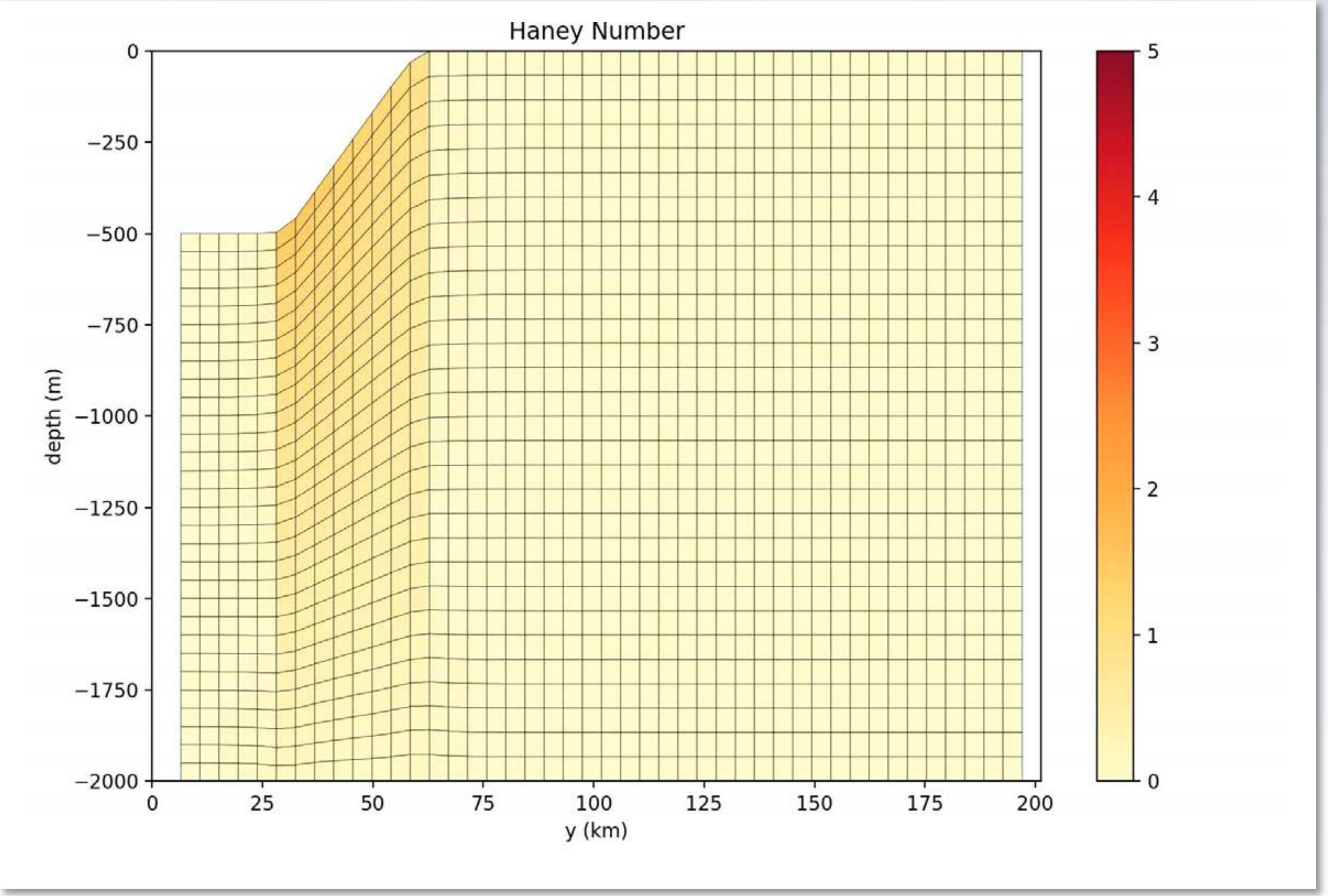



From Schmidtko et al. (2014)

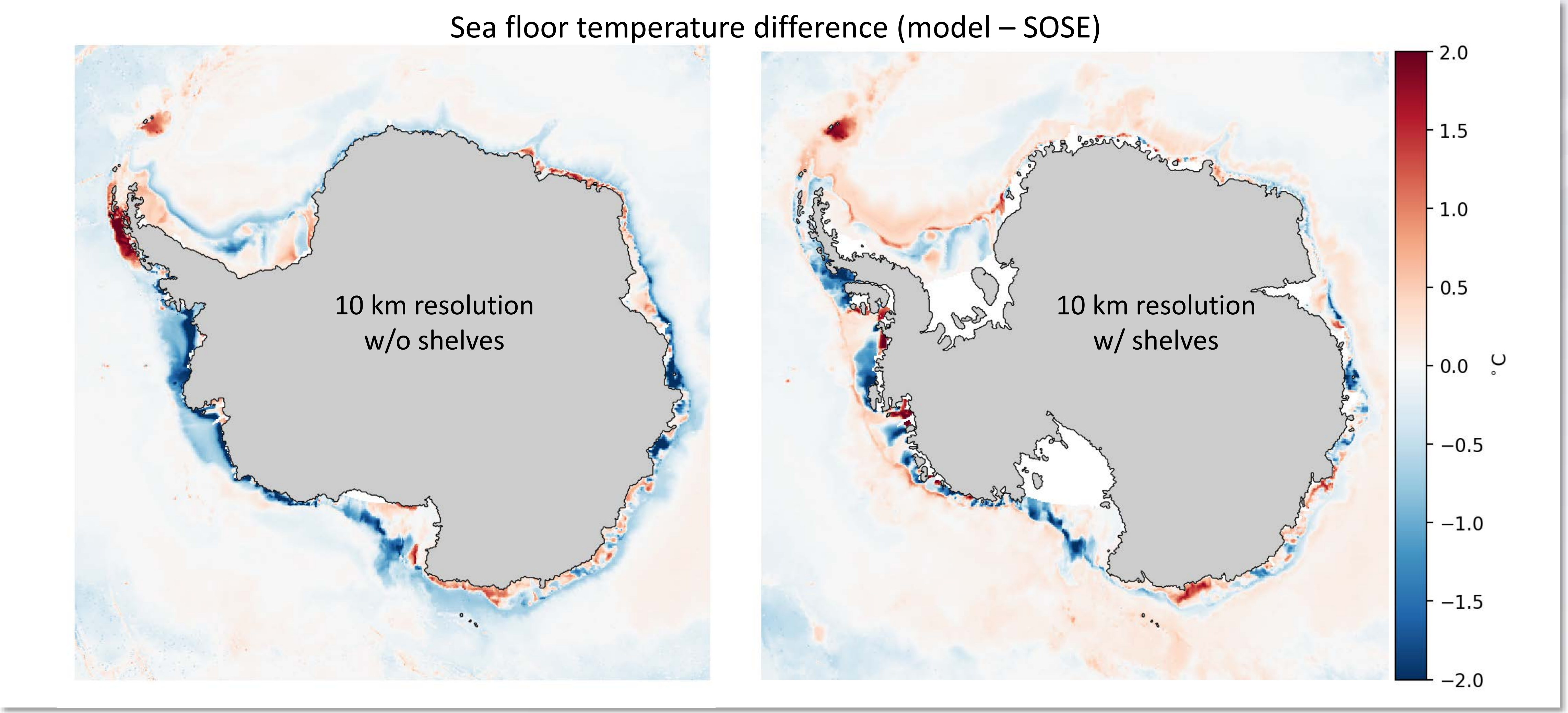



From Rignot et al. (2013)

# Ice shelves in E3SM

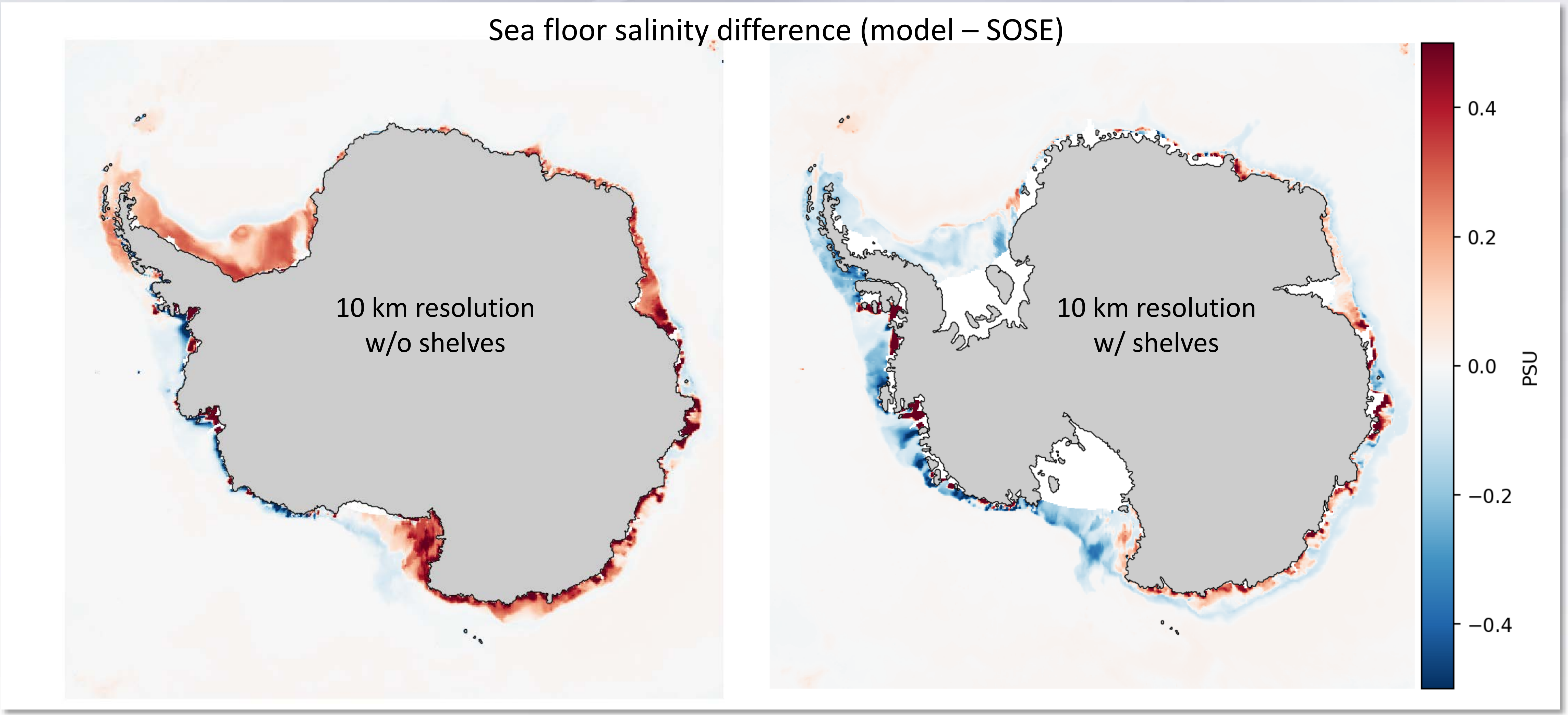


# Ocean temp. sensitivity to Ice Shelves in E3SM



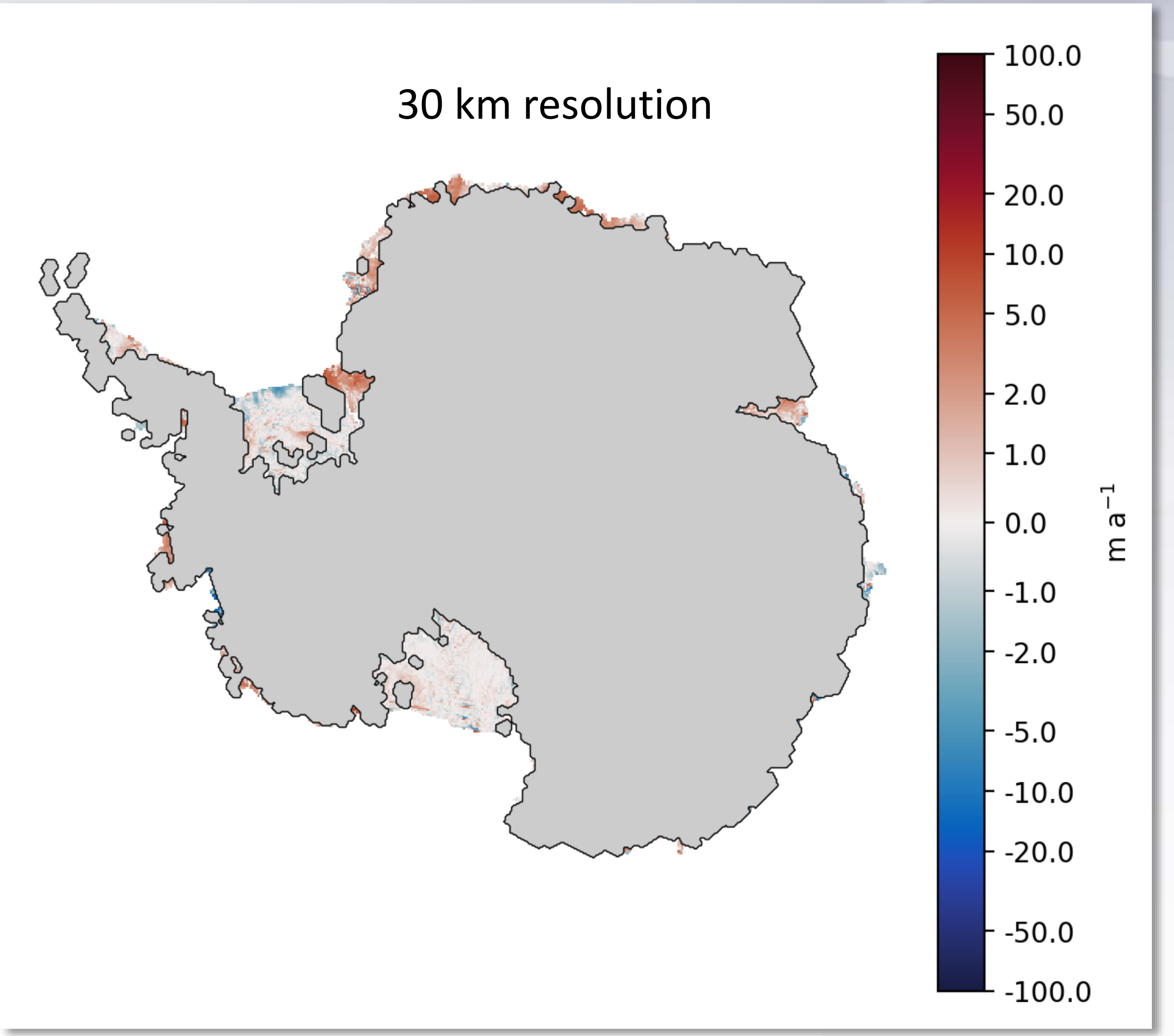

Biases relative to SOSE (Mazloff et al. 2010)

# Ocean salinity sensitivity to Ice Shelves in E3SM




Biases relative to SOSE (Mazloff et al. 2010)

# Melt rate sensitivity to resolution in E3SM




Biases relative to Rignot et al. (2013)

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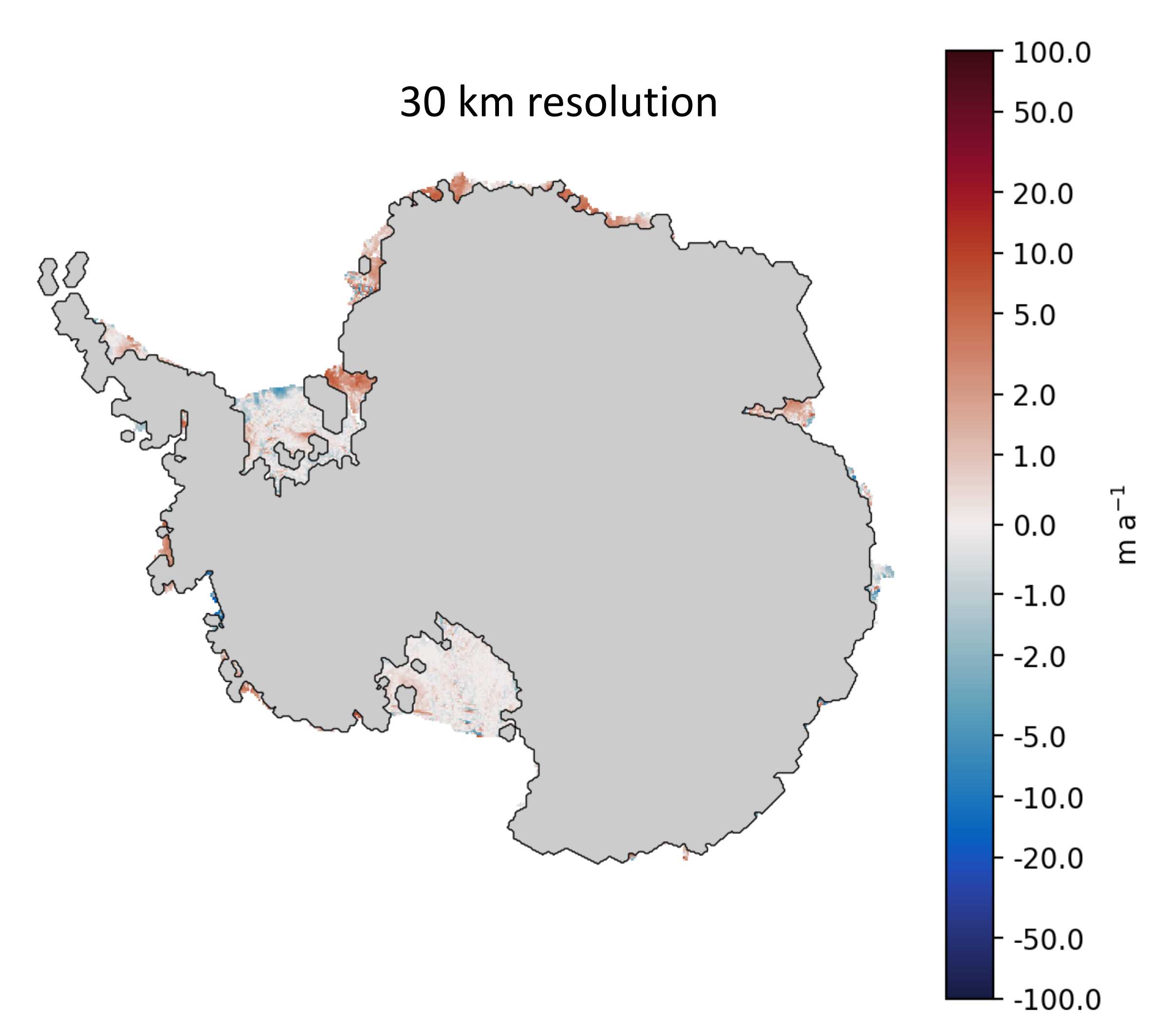
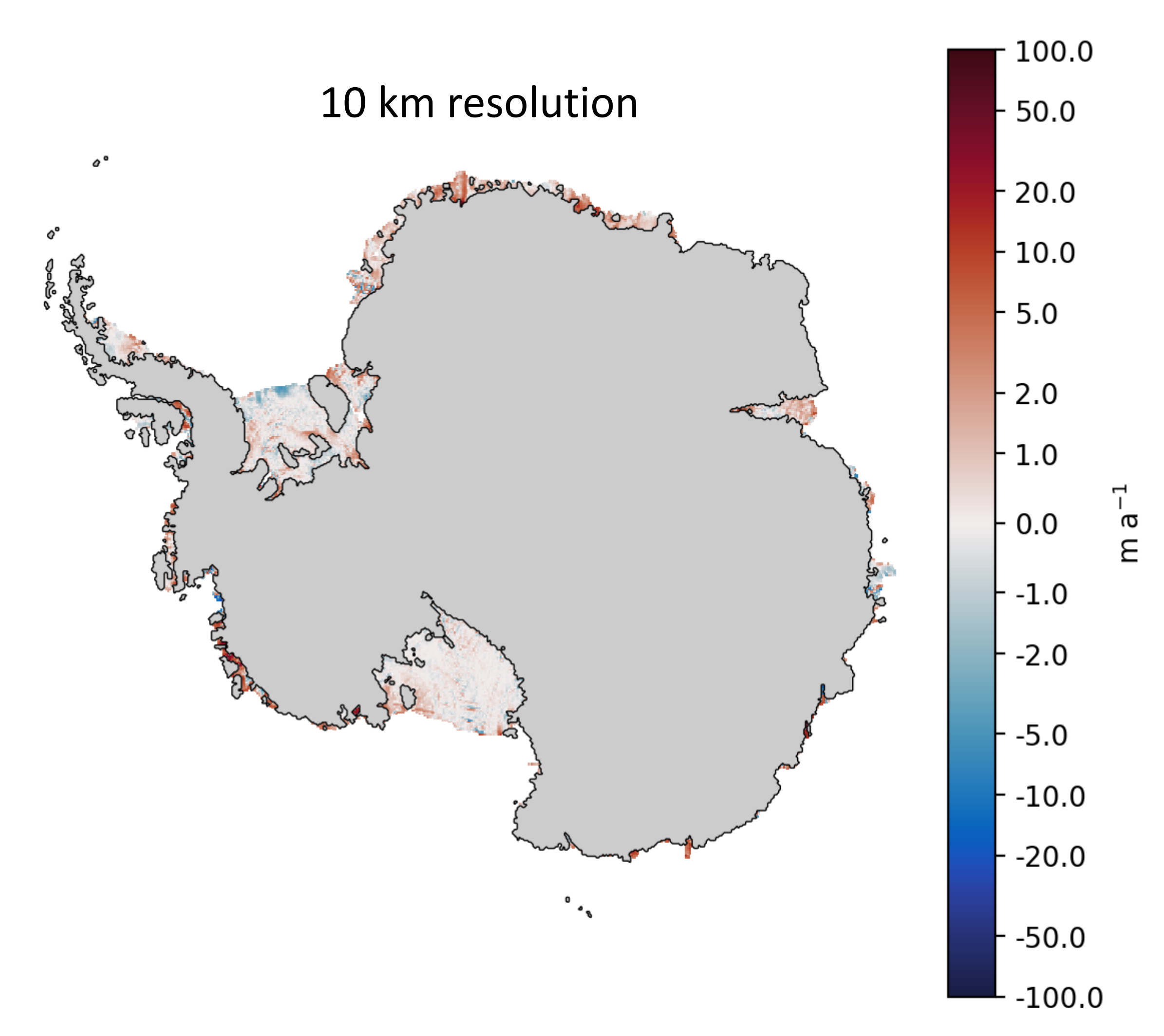
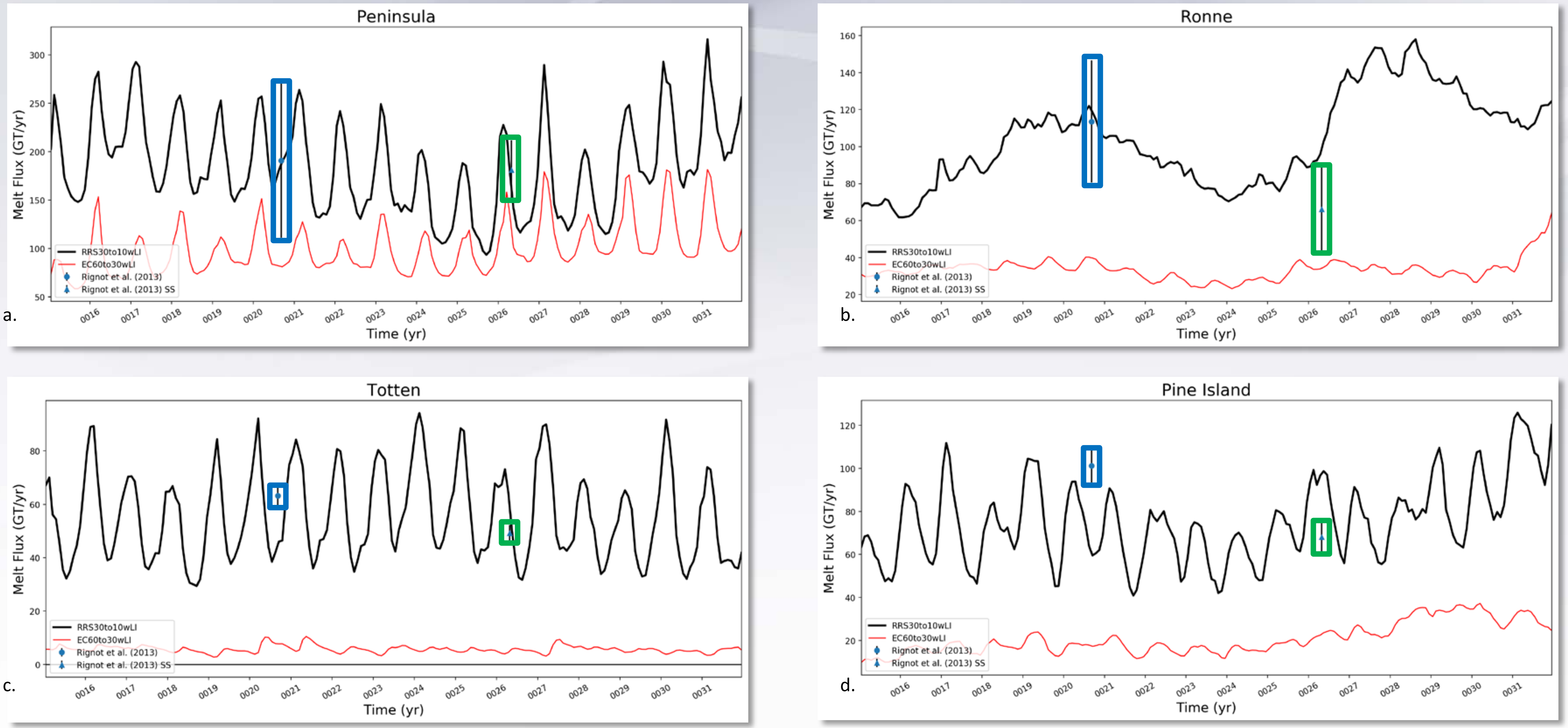


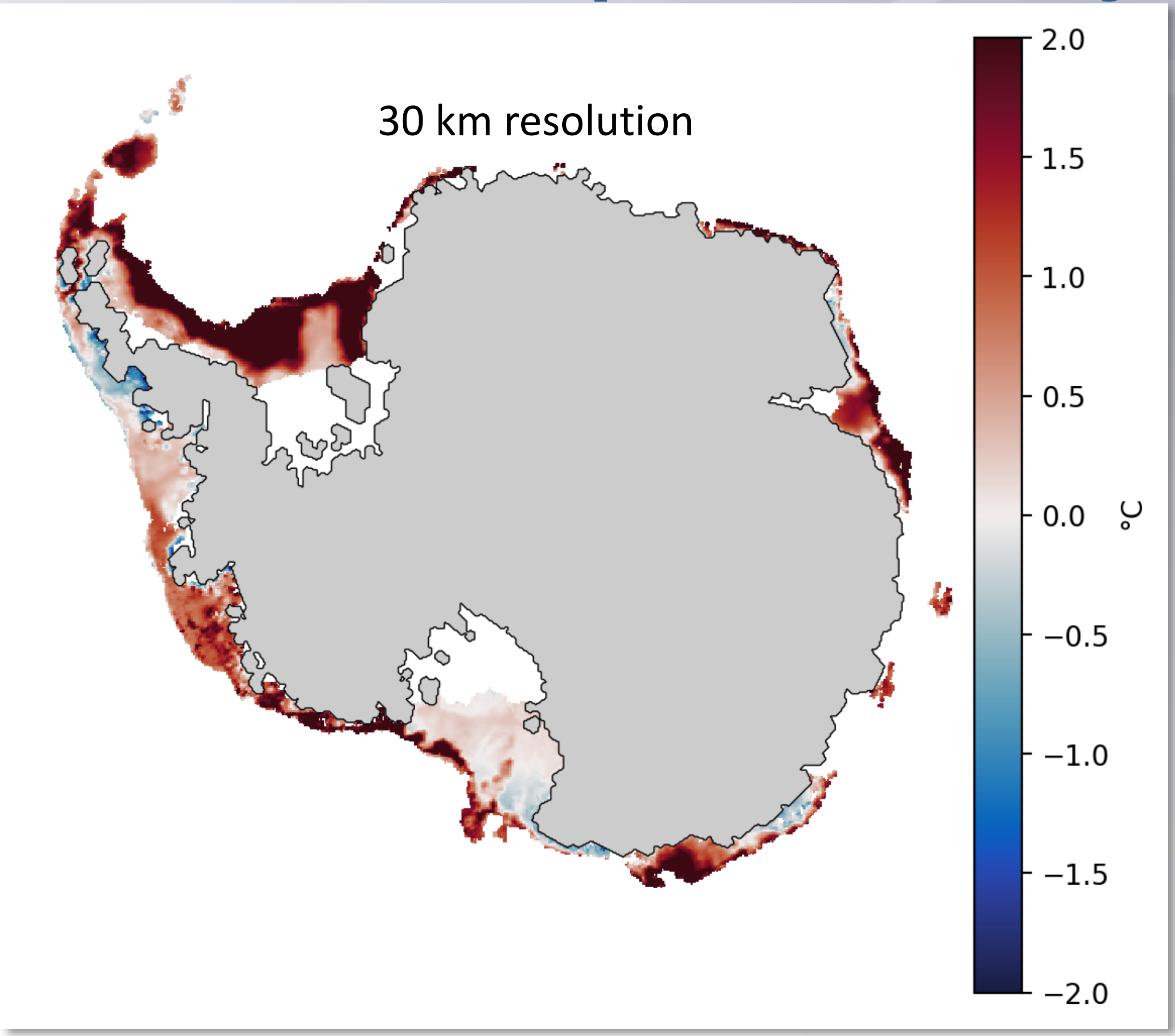

Biases relative to Rignot et al. (2013)

# Melt rate sensitivity to resolution in E3SM



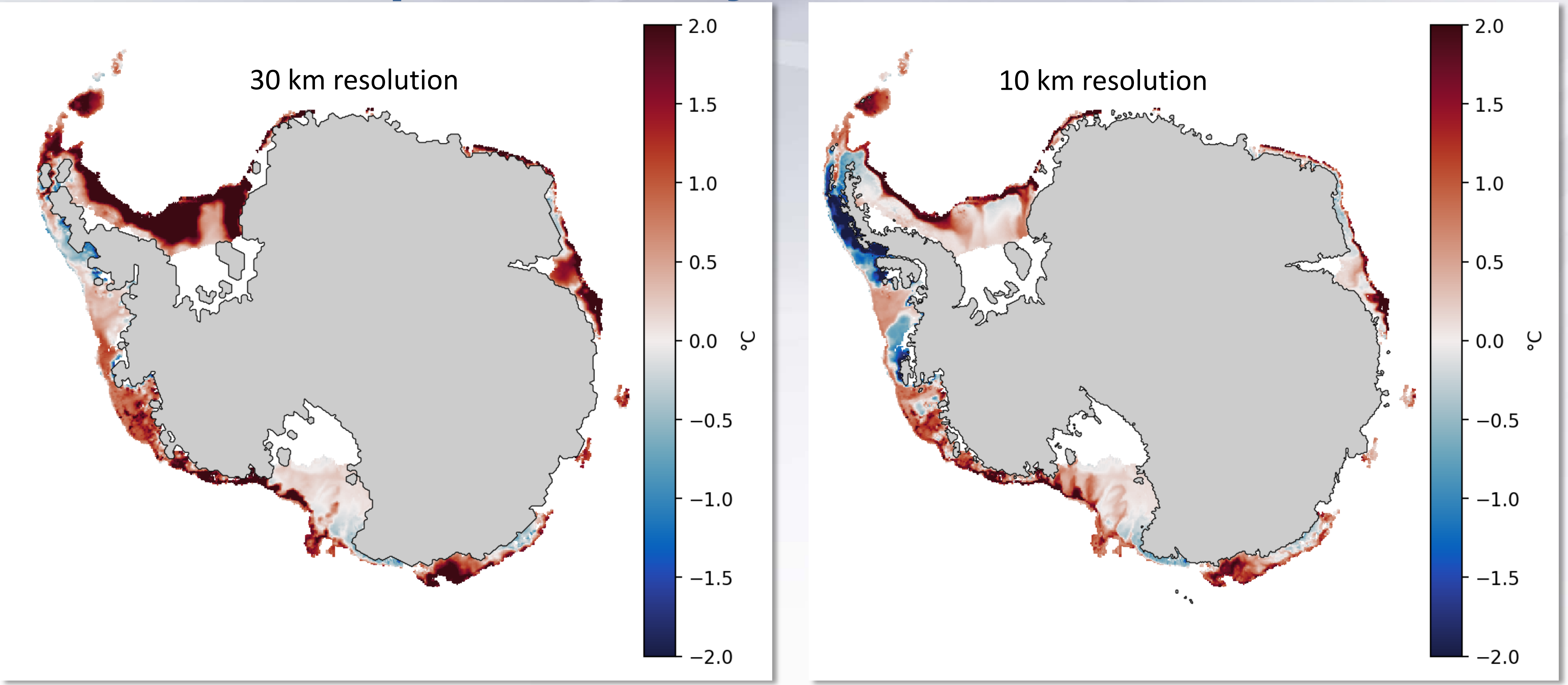

Obs: Rignot et al. (2013)

# Seafloor temp. sensitivity to resolution in E3SM



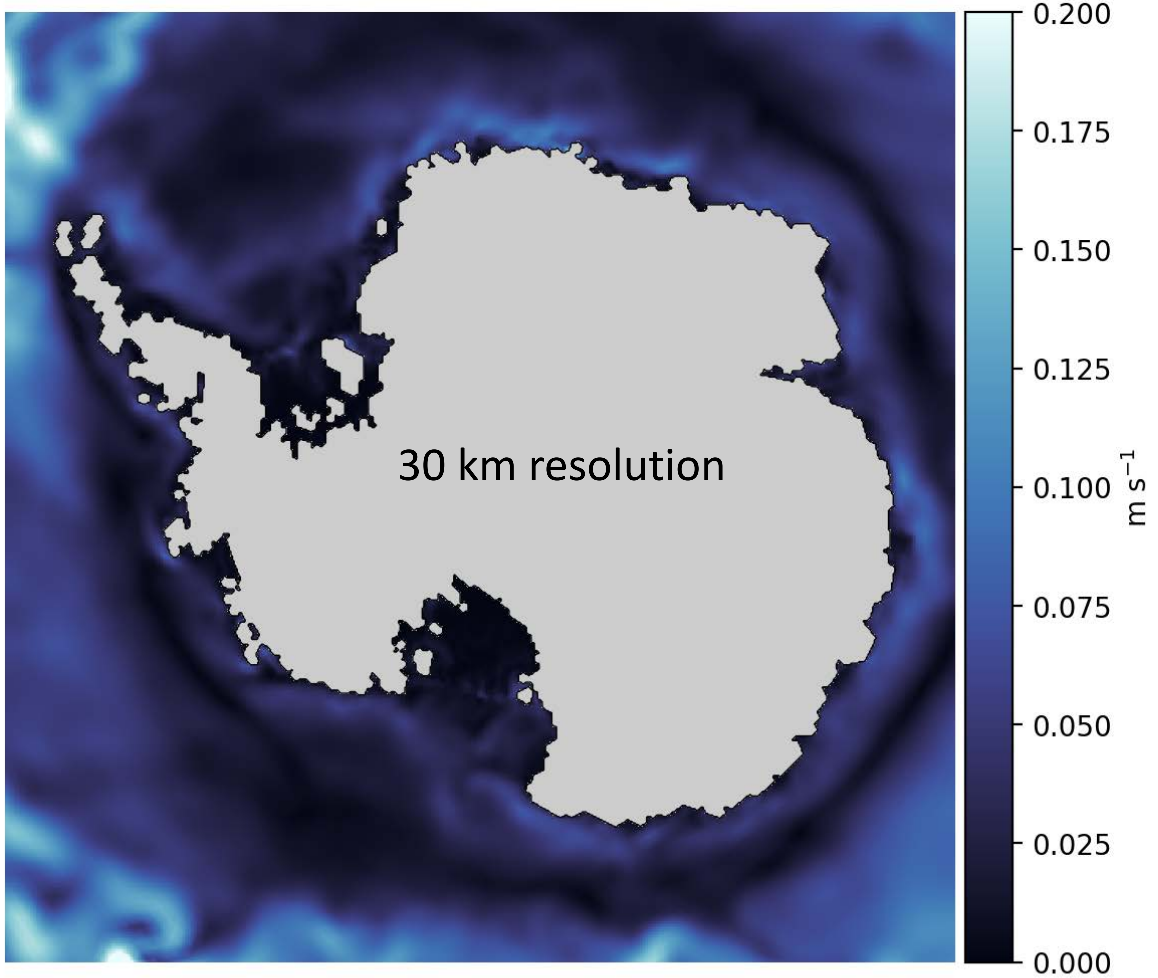

Biases relative to Schmidtko et al. (2014)

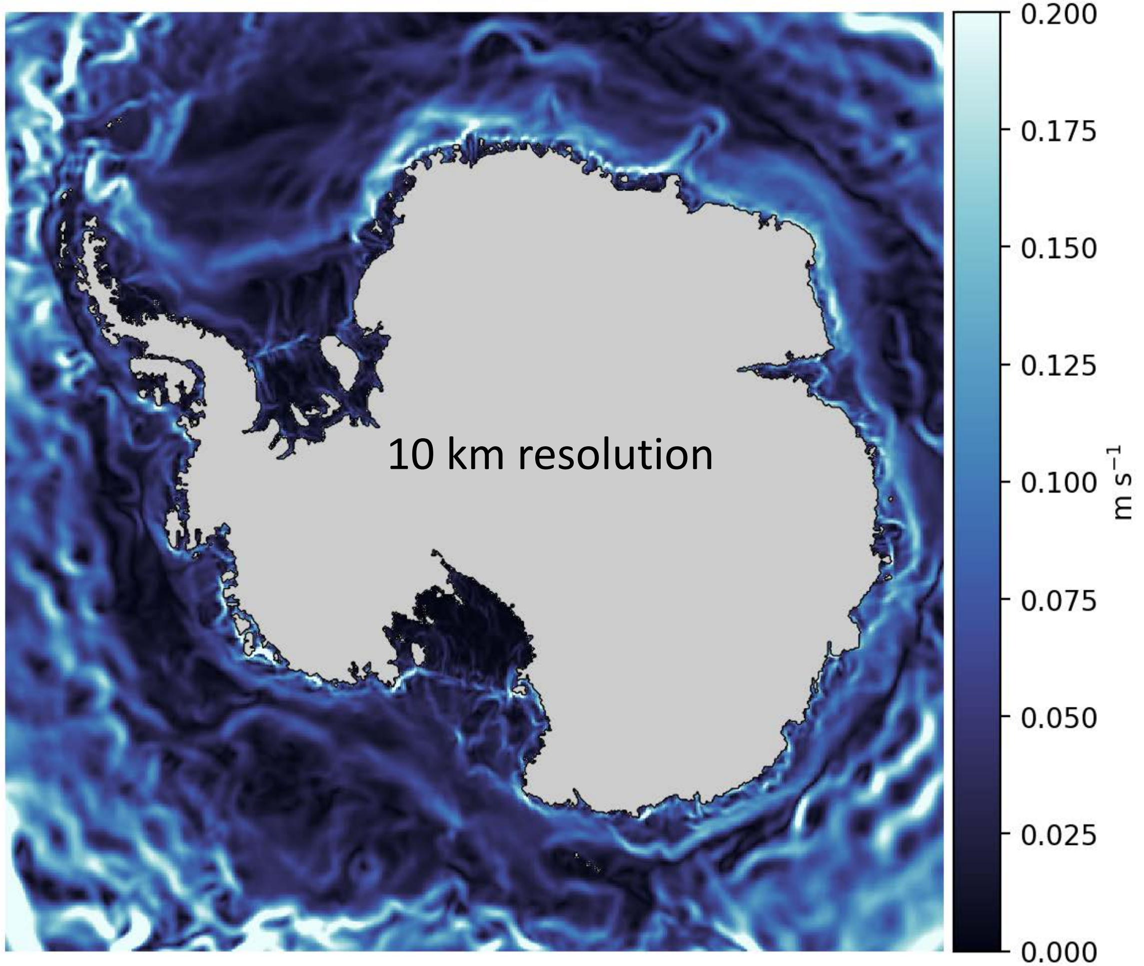
# Seafloor temp. sensitivity to resolution in E3SM




Biases relative to Schmidtko et al. (2014)

# Surface velocity sensitivity to resolution in E3SM




Biases relative to Schmidtko et al. (2014)

# Implementation of ice-shelf cavities in E3SM

- Vertical coordinate system:
  - constrained pressure-gradient errors
- Adjustment of sea-surface height:
  - must be consistent with ice pressure
- Parameter study:
  - Best-fit values for uncertain coefficients

# Horizontal pressure gradient with tilted coordinates

- Horizontal pressure gradient:

$$-\left.\frac{\partial P}{\partial x}\right|_z = -\rho_s g \frac{\partial \zeta}{\partial x} - g \int_z^{\zeta} \mathcal{J}(\rho, z) ds,$$

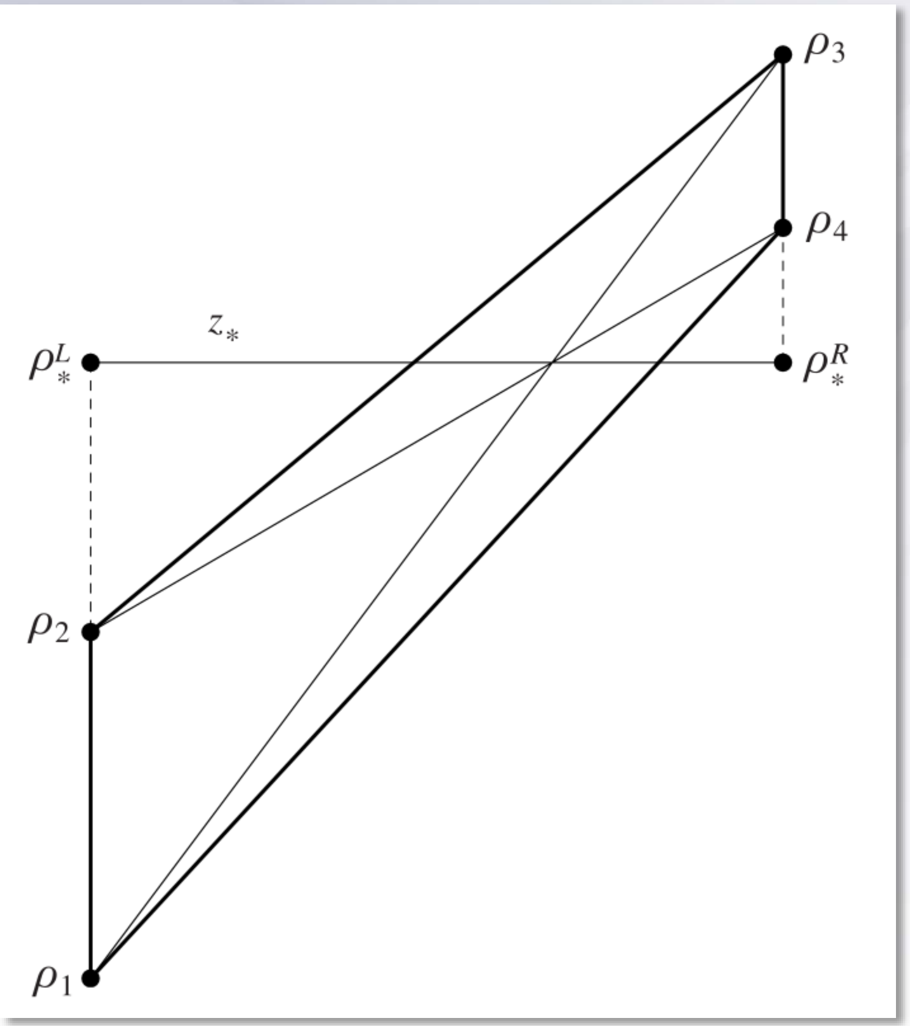
- Green's Theorem:

$$\iint_{\mathcal{A}} \mathcal{J}(\rho, z)\; dx\; ds = \oint \rho(\mathbf{k}, \mathbf{l}) dl,$$

- Nonlinear equation of state (EOS):

  ρ = ρ(S, Θ, p)

- EOS involves the pressure itself



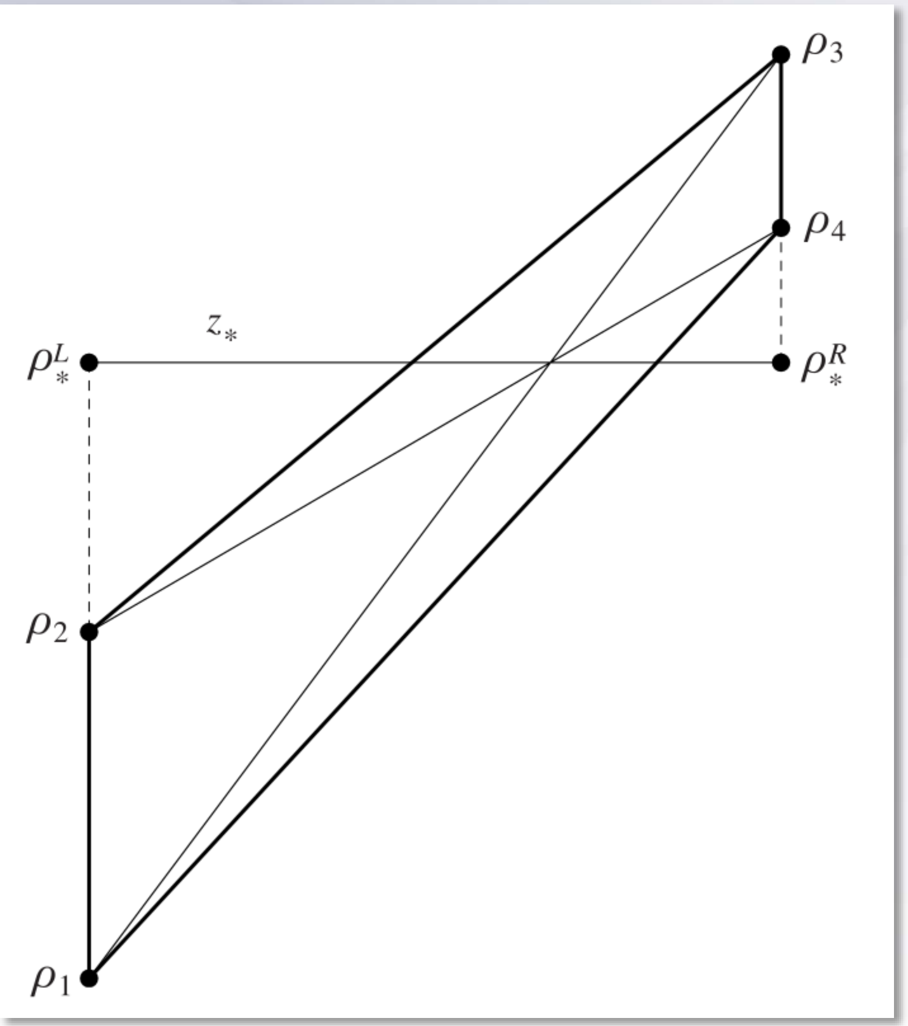

From Shchepetkin and McWilliams (2003)

# Horizontal pressure gradient with tilted coordinates

- Second-order discretization of

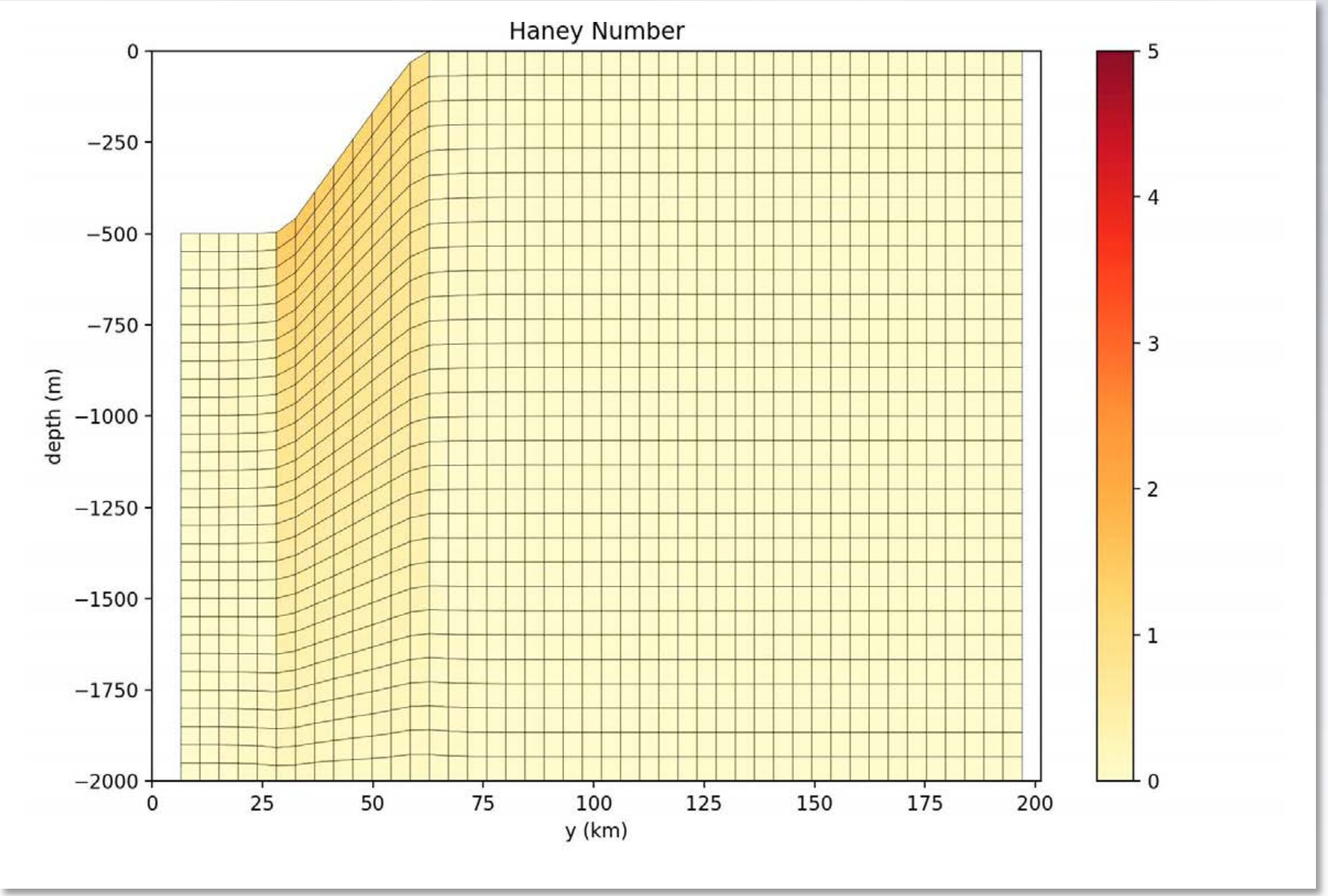
$$\oint \rho(\mathbf{k}, \mathbf{l})\, dl,$$

  leads to instability when Layers are both:
  - thin
  - strongly tilted
- Haney Number rx1: a non-dimensional measure of this effect (Haney 1991)



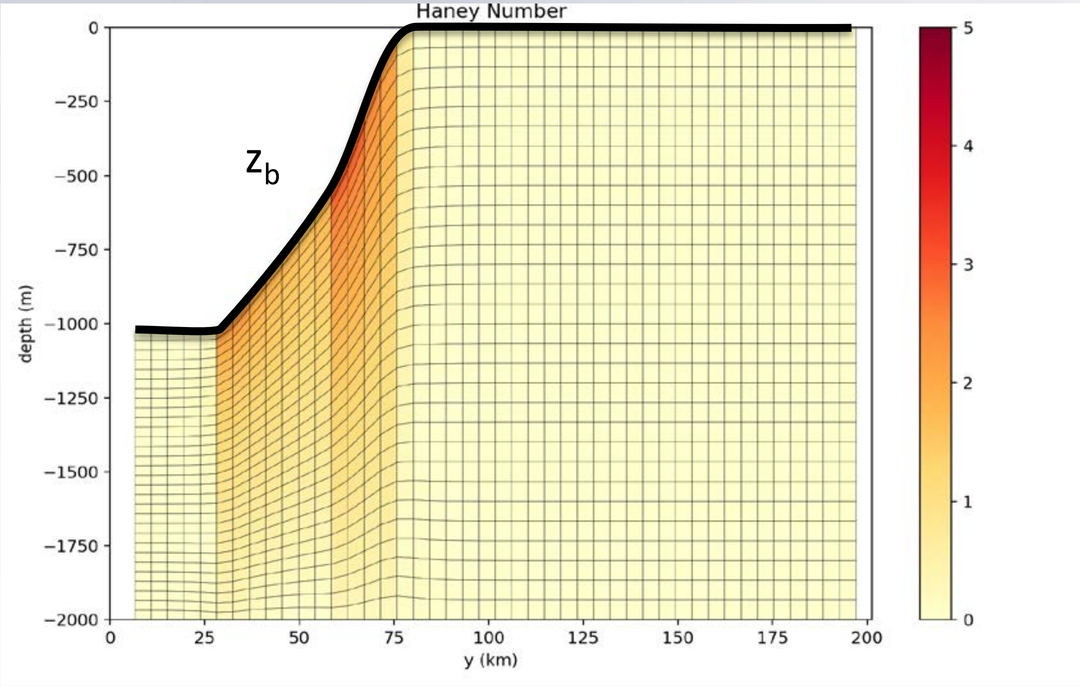

From Shchepetkin and McWilliams (2003)

# The Haney Number: rx1 ≤ 5



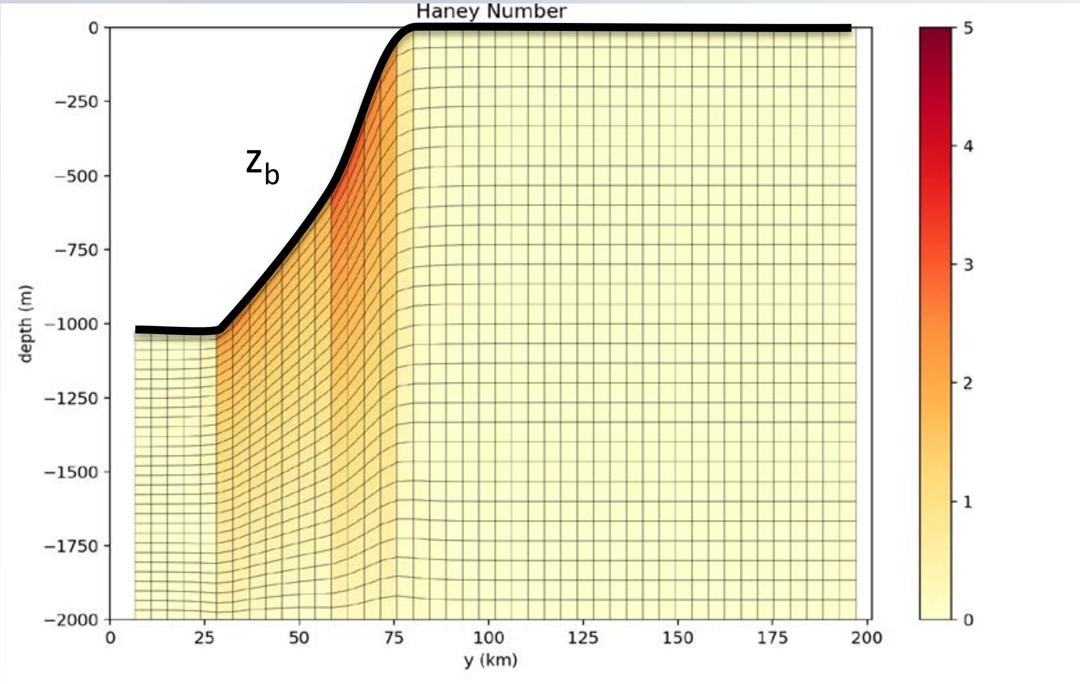
# Consistent sea surface height and ice pressure

- Ice pressure is the weight of the overlying ice shelf
- In equilibrium, balanced by ocean pressure
- Pressure at ice-ocean interface ($z_b$) changes by raising/lowering



# Consistent sea surface height and ice pressure

- Difficulties in finding equilibrium $z_b$:
  - density variation (horizontal and vertical)
  - Various possible equations of state
  - Various possible implementations of horizontal pressure gradient




- E3SM uses iterative adjustment of $z_b$ to minimize $dz_b$ /dt over the first hour of sim.

# Parameter Sensitivity Study at 30-km resolution

- 23 runs with 13 uncertain parameters
- Compared melt rates to observations (Rignot et al. 2013)
- Found 4 parameters with high sensitivity
- Determined best-fit values to minimize bias

Green's function method of Menemenlis et al. (2005):

- Assume perturbations in model state are linear in perturbed parameter values:

$$\boldsymbol{y}^d = \boldsymbol{G\eta} + \boldsymbol{\varepsilon}$$

- Find parameter values that minimize a cost function:

$$J = \boldsymbol{\varepsilon}^T \boldsymbol{R}^{-1} \boldsymbol{\varepsilon} = \sum_i \left( \frac{y_i^0 - x_i}{\sigma_i} \right)^2$$

- Best-fit parameter perturbations are computed as:

$$\boldsymbol{\eta}_{fit} = \left( \boldsymbol{G}^T \boldsymbol{R}^{-1} \boldsymbol{G} \right)^{-1} \boldsymbol{G}^T \boldsymbol{R}^{-1} \boldsymbol{y}^d$$

# Parameter Sensitivity Study at 30-km resolution

| Parameter Name | Control Value | Perturbed Value | RMS Melt Diff. (Rignot et al. 2013) | Best-fit Value |
|---|---|---|---|---|
| ctrl | N/A | N/A | 3.274 | N/A |
| land_ice_flux_attenuation_coefficient | 10 | 5 | 3.274 | 2.56 |
| | | 15 | 3.259 | |
| land_ice_flux_boundarylayerthickness | 10 | 5 | 3.283 | 0.351 |
| | | 15 | 3.268 | |
| **land_ice_flux_jenkins_heat_transfer_coefficient**<br>**land_ice_flux_jenkins_salt_transfer_coefficient** | 0.011<br>$3.1 \times 10^{-4}$ | 0.005<br>$1.4 \times 10^{-4}$ | **2.046** | 0.00295<br>$8.42 \times 10^{-5}$ |
| | | 0.02<br>$5.7 \times 10^{-4}$ | **4.685** | |
| land_ice_flux_rms_tidal_velocity | 0.05 | 0.01 | 2.806 | 0.133 |
| | | 0.1 | 3.983 | |
| **land_ice_flux_topdragcoeff** | 0.0025 | 0.001 | **2.488** | $4.48 \times 10^{-3}$ |
| | | 0.01 | **4.637** | |
| cvmix_kpp_criticalbulkrichardsonnumber | 0.25 | 0.2 | 3.306 | 0.0558 |
| | | 1.0 | 2.895 | |
| cvmix_kpp_use_enhanced_diff | true (1.0) | false (0.0) | 3.368 | true (0.598) |
| cvmix_kpp_surface_layer_extent | 0.1 | 0.07 | 3.173 | 0.0114 |
| | | 0.14 | 3.353 | |
| **cvmix_background_diffusion** | 0.0 | $10^{-5}$ | 3.128 | $7.73 \times 10^{-5}$ |
| | | $10^{-4}$ | **2.470** | |
| cvmix_background_viscosity | $10^{-4}$ | $10^{-5}$ | 3.267 | $9.13 \times 10^{-6}$ |
| standardgm_tracer_kappa | 1800 | 600 | 3.236 | 1620 |
| | | 1200 | 3.440 | |
| salinity_restoring_constant_piston_velocity | $1.585 \times 10^{-6}$ | $7 \times 10^{-7}$ | **4.570** | $2.45 \times 10^{-6}$ |
| | | $3 \times 10^{-6}$ | **4.106** | |

# Ongoing work: Ice-ocean coupling in E3SM

Ingredients needed:

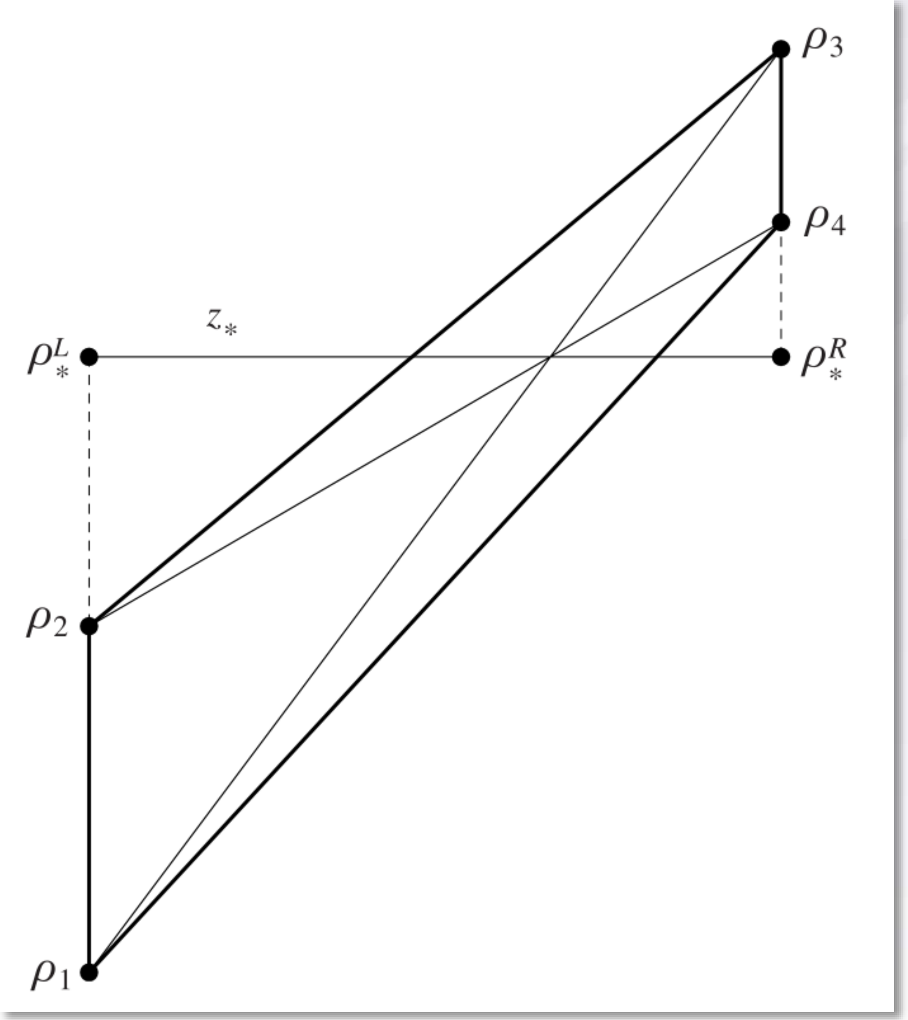
- Higher-order pressure gradient
  - thinner, more tilted layers
- Wetting-and-drying
  - Allows ice to advance and retreat

# Higher-order pressure gradient

- Accurate evaluation of contour integral:

$$\oint \rho(\mathbf{k}, \mathbf{l})\, dl,$$

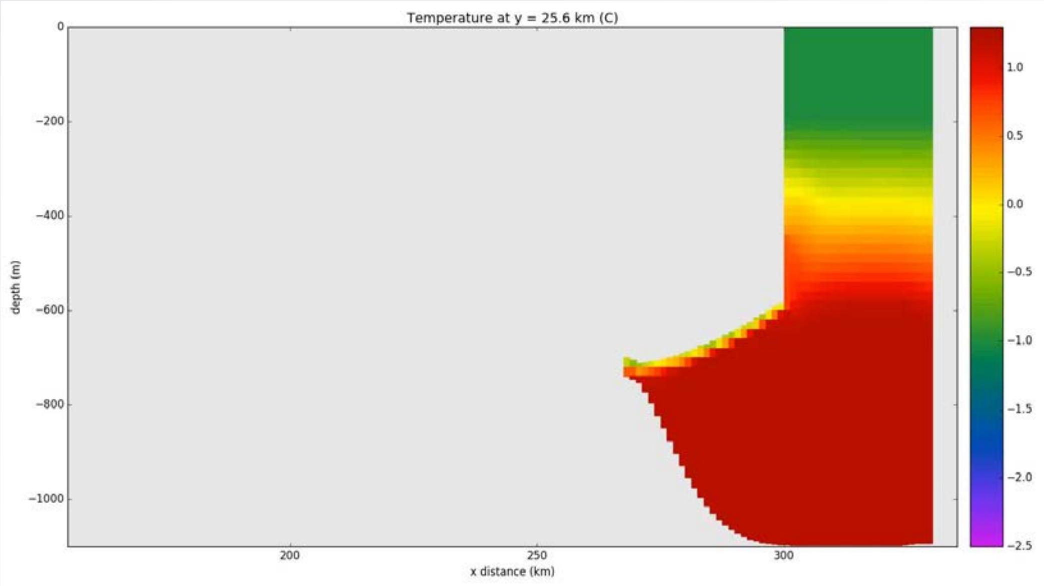
- Known approaches:
  - Choose EOS so integral is analytic (e.g. Adcroft et al. 2008)
  - high-order Gaussian quadrature (e.g. Engwirda et al. 2016)
- Should allow rx1 ≫ 5




From Shchepetkin and McWilliams (2003)

# Wetting and Drying Scheme

- Thin film, O(cm) or less, of ocean in “dry” regions
- “Dry” cells allow mass fluxes in but prevent fluxed out
- Implemented for coastal sea-level change
- Work in progress: ice sheet advance/retreat:
  - Increased ice pressure from ice advance will cause drying
  - Decreased pressure from ice retreat will allow wetting




Example of ice-shelf retreat from a POPSICLES simulation

# Summary

- E3SM v1.0 code released in April
  - low, medium, and high-resolution configurations included
  - Ice-shelf configurations included: use at your own risk

- Ice shelves will (hopefully) be default in E3SM v2.0
  - improve ocean properties, particularly at high resolution
  - allow projections of Antarctic melt rates and ultimately ice mass loss

- Dynamic coupling with land-ice model is ongoing
  - higher-order pressure gradient
  - wetting and drying

eddy activity in high-resolution ocean simulation